Proc. 23rd Winter Workshop on
Nuclear Dynamics (2007) 000–000

23rd Winter Workshop on Nuclear Dynamics
Big Sky, Montana, USA
February 11–18, 2007

Direct photon-jet correlations in relativistic heavy ion collisions

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Abstract. Suppression of high-p_T hadrons by the dense nuclear medium produced in heavy-ion collisions has been repeatedly demonstrated in measurements of the nuclear modification factor R_{AA} at RHIC, suggesting considerable medium-induced energy loss. However, a probe of the nuclear fireball is sought that allows more discrimination between different suppression/energy loss mechanisms than R_{AA} provides. Hard QCD processes involving final-state prompt photons can be studied with azimuthal jet correlation techniques, offering an important opportunity to improve understanding of energy loss and jet fragmentation, since photons are essentially unaffected by the nuclear matter and their energy approximately balances that of the away-side jet. A description of the process of obtaining γ_{direct}-$h^{\pm}$ jet pair correlations is presented in addition to an update on recent results from the PHENIX experiment.

Keywords: QCD, photon, jet
PACS: 25.75.Dw, 25.75.Gz

1. Introduction

One of the most striking results released by the RHIC experiments to date has been the large suppression of outgoing hadrons in relativistic A+A collisions compared to expectations from binary-scaled p+p collisions, suggesting a high degree of opacity of the nuclear material to partons [1, 2]. This suppression is conventionally explained in the context of partonic energy loss in a high-density medium of color charges [3]. A compelling demonstration of single particle suppression is given by yield measurements of high-p_T π^0s and η mesons originating from jet fragmentation in the medium. The nuclear modification factor R_{AA} compares these yields to a baseline yield from $p+p$ events, scaled to match the system size of nuclear collisions:

$$R_{AA}(p_T, y) = \frac{d^2N^{AA}/dp_T dy}{T_{AA}(\mathbf{b})d^2\sigma_{NN}/dp_T dy}, \tag{1}$$

The nuclear thickness function T_{AA} is the projection of the nuclear overlap region's density profile onto the azimuthal plane, varying with impact parameter $\mathbf{b}$. The plot of this quantity in figure 1 shows that at high p_T, π^0s are suppressed by roughly a factor of five in $Au+Au$ compared to the $p+p$ expectation. The large color-

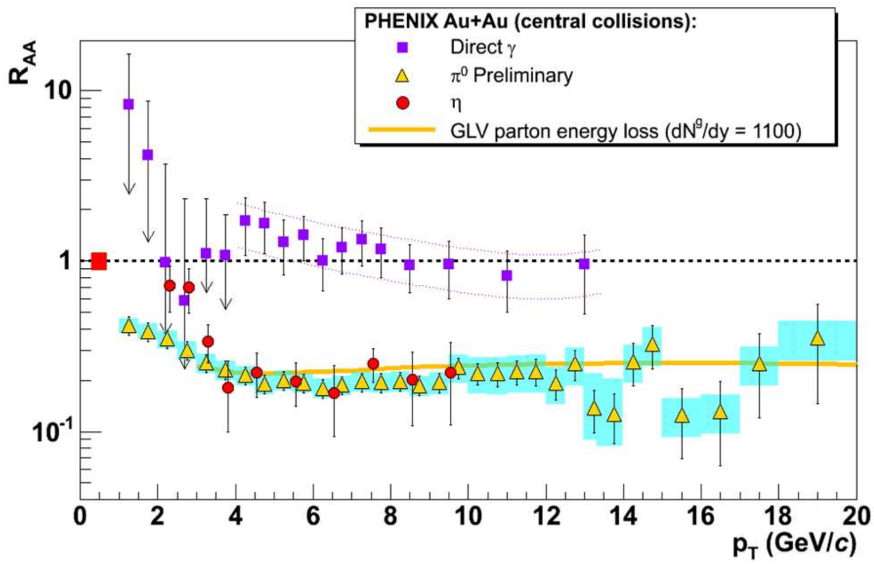

Fig. 1. Nuclear modification of π^0, η, and direct photons in central $\sqrt{s_{NN}} = 200$ GeV $Au+Au$ collisions. Neutral meson yields are suppressed by up to a factor of five, while photon yields are unmodified.

charge opacity suggested by this measurement indicates that the energy loss depends strongly on the path length of the outgoing parton through the medium before fragmentation; consequently, the dominant majority of these high p_T particles is thought to originate from hard-scattering vertices in or near a rarefied coronal region at the surface of the medium rather then escaping from its depths [4]. Importantly, figure 1 also demonstrates that photons produced directly in high-Q^2 processes suffer no such suppression, indicating that the medium is in fact transparent to photons at these energies.

Although a large degree of partonic energy loss is suggested by R_{AA} measurements, the precise nature of this energy loss is unclear from such a quantity, since R_{AA} is ultimately a convolution of (a) the QCD hard-scattering cross-section, (b) the parton's coupling to the color charges in the medium, (c) the density of these color charges, and (d) the vacuum fragmentation function of the final-state parton. There is therefore very little detailed tomographic information about the dense, opaque core of the nuclear fireball contained in a measurement of particles produced primarily near its surface, as argued in [5]. Figure 2 shows calculations from this reference in which a collection of several widely varying energy loss models is demonstrated to be compatible with the data, suggesting that a more discriminating probe is required.

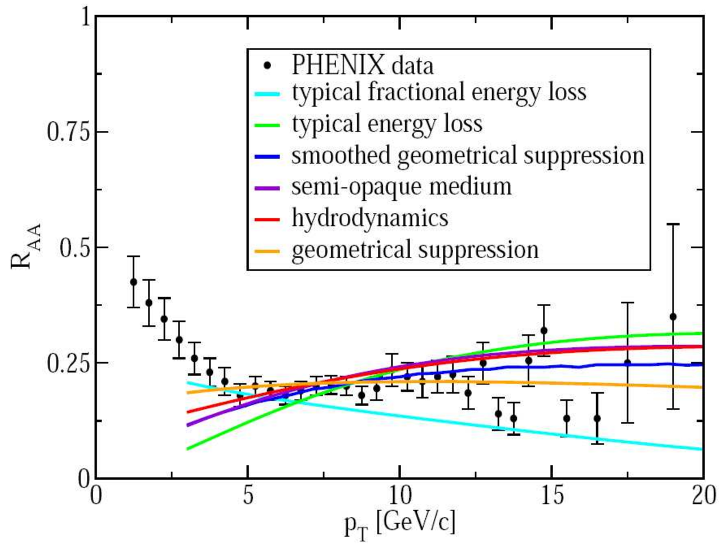

Fig. 2. Calculations from [5] based on a variety of different energy loss mechanisms are compatible with experimental data, suggesting that R_{AA} lacks power to effectively constrain theoretical models.

1.1. Motivation for γ-jet correlation measurements

Observation of medium-induced jet shape and yield modifications via di-jet correlations goes a step further than R_{AA} measurements as a tool to study medium effects, and significant progress has been made in this respect [6, 7], but these techniques ultimately suffer from a similar surface bias, since the reference "trigger" hadron is itself most likely a jet fragment that has been produced near the surface. Isolating information about the interior of the fireball would therefore require a deconvolution of several nontrivial effects.

It is in principle possible to exploit the observation from figure 1 that photons couple very weakly to the medium by studying hard processes with prompt photon final states. It has been anticipated for some time that jet correlation measurements involving direct photon triggers could quantify the softening of the fragmentation function of the away-side jet [8]. γ-jet events are an ideal experimental probe since the energy of the trigger photon can be known to high precision, and at leading order the transverse energy of the photon is equivalent to that of its back-to-back parton, modulo k_T smearing effects. Moreover, a hard-scattered prompt photon is expected to escape from any scattering position within the medium with essentially all of its initial energy, eliminating or vastly reducing the surface bias effects inherent in di-jet analyses. For these reasons, jet correlations with direct photon trigger particles provide an automatically calibrated measure of medium-induced modification of partonic fragmentation.

2. Direct photon sources and measurement expectations

Inclusive photon yields are dominated by contributions from two general categories: photons originating from hadronic decays, and direct photons [9]. Approximately 75-90% of decay photons come from the $\pi^0 \to 2\gamma$ process, followed by $\eta \to 2\gamma$, with contributions of order 2 percent from η', ω, and other decays.

Direct photons with $p_T > 5$ GeV/c are primarily produced by hard leading-order QCD processes such as Compton scattering ($qg \to q\gamma$), with small contributions from $q\bar{q}$ annihilation ($q\bar{q} \to 2\gamma$ or $q\bar{q} \to g\gamma$) as well from higher-order processes such as bremsstrahlung and fragmentation. The higher-order contributions diminish to a small fraction of the direct photon yield with increasing p_T [10].

Since the $qg \to q\gamma$ process is by far the biggest contributor to γ-jet correlations at $p_T > 5$ GeV/c, it is expected that there will be a measurable number of charged hadrons produced opposite the direct photon trigger, but there will be almost no $h^{\pm}$ jet partners correlated with the trigger's direction on the near-side jet, resulting in the absence or diminution of any near-side jet peak compared to $\gamma_{inclusive}$-$h^{\pm}$ correlations. At lower particle energies, however, a small near-side jet peak due to radiated or fragmented photons could potentially be observed, provided that adequate experimental sensitivity is achievable.

The proportion of direct photons in an inclusive sample is measured by the observable R_γ, essentially defined as the ratio of inclusive to decay photon yields, $\gamma_{incl}/\gamma_{decay}$. Clearly, under the assumption $\gamma_{incl} = \gamma_{direct} + \gamma_{decay}$, a value of $R_\gamma > 1$ indicates the presence of direct photons in the sample. PHENIX measurements of R_γ in Au+Au collisions reflect that R_γ increases considerably (1) as photon p_T increases, and (2) as collisions become more central, where the hadrons responsible for decay photon backgrounds become more suppressed. A significant experimental challenge is therefore to distinguish a statistically significant sample of the rare energetic direct photon-jet events from a background containing many decay photons.

3. Analysis methods

While techniques for identifying jets event-by-event have been successfully implemented in p+p collisions, the high-multiplicity environment of A+A collisions is more favorable to statistical methods such as angular pair correlations, which involve measuring the distribution of azimuthal $\Delta\phi$ angles between a high-p_T "trigger" particle in an event and all $h^{\pm}$ tracks from the event in a given p_T bin. A mixed-event combinatorial background is divided out, resulting in an angular correlation function containing contributions from jets and collective flow of the medium. The flow background is removed by the zero-yield-at-minimum method [6], which works with good accuracy at the high p_T values of this analysis, where the jet peaks are well-separated and the flow background is a minor contribution.

3.1. Direct γ-jet yields: subtraction method

The result of a correlation analysis is then the per-trigger conditional jet pair yield $Y \equiv (1/N^{trig})\, dN^{pairs}/d(\Delta\phi)$. Under the two-source assumption of section 2, the inclusive γ-$h^{\pm}$ per-trigger yield is the weighted sum of direct and decay components:

$$Y_{incl} = \frac{\gamma_{dir}}{\gamma_{incl}} Y_{dir} + \frac{\gamma_{decay}}{\gamma_{incl}} Y_{decay}. \tag{2}$$

If the weight factors are expressed in terms of $R_\gamma = \gamma_{incl}/\gamma_{decay}$, equation 2 can be written as

$$Y_{dir} = \frac{R_\gamma Y_{incl} - Y_{decay}}{R_\gamma - 1}. \tag{3}$$

The subtraction method therefore requires an experimental determination of R_γ in addition to the γ_{incl}-$h^{\pm}$ and γ_{decay}-$h^{\pm}$ per-trigger yields to arrive at a direct photon jet result. An example of the input correlations is shown for 9-12 GeV/c triggers in figure 3. Some scatter is visible near $\Delta\phi = \pm\pi/2$, the position of pair-acceptance minima in the PHENIX central arm detectors. The jet peaks are nevertheless clearly resolvable at these momenta and are shown with Gaussian fits centered at $\Delta\phi = 0$ and π.

3.2. Background measurement and calculation

A primary experimental challenge in using the subtraction method described in eq. 3 is identifying the shape and normalization of Y_{decay}. Because the majority of decay photon triggers originate from π^0 parents, Y_{decay} is calculated from π^0-$h^{\pm}$ pairs, and contributions from all other hadronic parents is neglected. A γ_{decay}-$h^{\pm}$ pair distribution is produced from a weighted summation over all π^0-$h^{\pm}$ pairs, where the weight is calculated according to the π^0's probability to yield a photon residing within a specified p_T range. The weighting function, shown in figure 4, is determined solely by decay kinematics for a perfect detector; however, corrections for finite energy resolution and π^0 reconstruction efficiency tend to modify

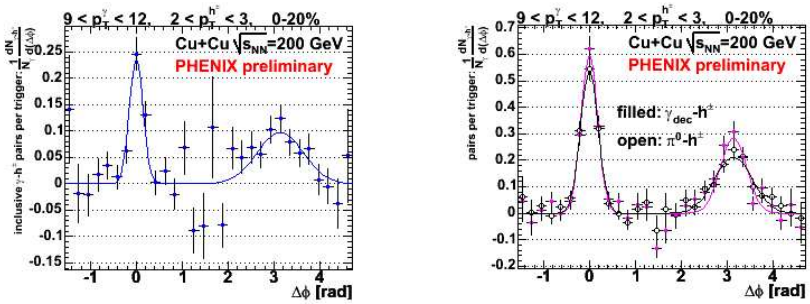

Fig. 3. Examples of two components required to obtain direct γ-$h^{\pm}$ per-trigger jet pair yields in Cu+Cu collisions. Left: γ_{incl}-$h^{\pm}$ per-trigger yield. Right: γ_{π^0}-$h^{\pm}$ per-trigger yield calculated from π^0-$h^{\pm}$ pairs.

its shape. Extensive tests with the PYTHIA event generator confirm that the π^0-$h^{\pm}$ pair-weighting method can reproduce the shape and normalization of the true γ(from π^0)-$h^{\pm}$ per-trigger yield to within 1-2%, where even this small discrepancy can be improved by properly accounting for decay-angle and acceptance effects.

Despite the high accuracy of the π^0-$h^{\pm}$ weighting procedure, further PYTHIA tests have shown that γ(from π^0)-$h^{\pm}$ overestimates the true γ_{decay}-$h^{\pm}$ yield by a few percent, implying that the contribution from η-$h^{\pm}$ and possibly other correlations must be accounted for. An unfortunate feature of the subtraction method is that any error in Y_{decay} is propagated to the Y_{direct} result with a magnification that grows sharply as $R_\gamma \to 1$. Thus, for example, Y_{direct} distributions measured by the subtraction method in lower-p_T or more peripheral events, particularly in smaller collision systems, suffer from a large over-subtraction if Y_{decay} is overestimated by just a few percent.

Just prior to this conference, two effects were discovered to be underestimated with respect to their influence on the subtracted Y_{direct} result: (1) finite energy resolution of the PHENIX electromagnetic calorimeter and (2) failure to account for η-$h^{\pm}$ correlations as described above. Corrections are currently in development, but in the meantime a systematic error has been placed on the final result to account for the second systematic bias. The magnitude of the systematic error is gauged by an observation from PYTHIA simulations that artificially increasing R_γ by 10% compensates for bias (2) and recovers the true Y_{direct}. This is clearly a temporary measure and reflects no additional uncertainty on R_γ; it is an effective procedure to compensate for a known bias of the subtraction method, and work is currently under way to refine the method with more rigorous procedures.

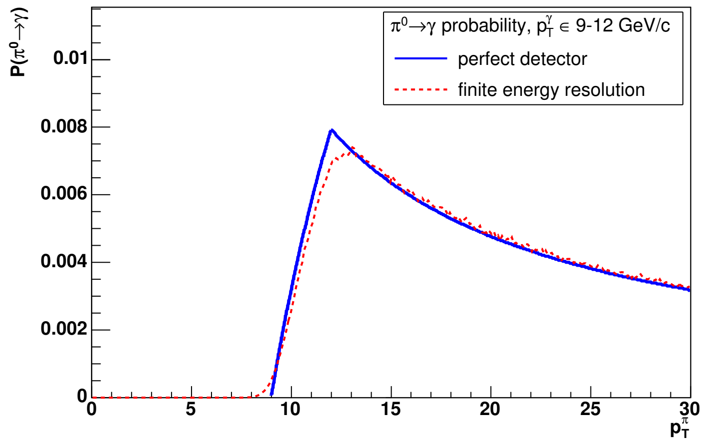

Fig. 4. Probability for a π^0 to decay into a photon with $9 < p_T^\gamma < 12$ GeV/c as a function of π^0 p_T. A low-side tail results from accounting for energy resolution effects.

4. Results

The final Y_{direct} results from the subtraction method are shown in figure 5 for central and mid-central Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV. A measurement of R_γ has been published by the PHENIX collaboration for Au+Au [11], but a Cu+Cu R_γ measurement is currently still in preparation. An estimation of R_γ is therefore interpolated from Au+Au data, based on the dependence of R_γ on π^0 (and η) suppression: if two different collision systems suppress neutral mesons at the same rate, then they should have comparable R_γ values. In other words, the assumption is made that since R_γ scales with $\langle N_{part} \rangle$, then $R_\gamma(30-50\%)_{Au+Au} \simeq R_\gamma(0-20\%)_{Cu+Cu}$ and $R_\gamma(50-60\%)_{Au+Au} \simeq R_\gamma(20-40\%)_{Cu+Cu}$. This approximation will of course become unnecessary once a reliable measurement of R_γ becomes available in the Cu+Cu data.

5. Conclusions

More statistics will be required to gain detailed information about Y_{direct}, but even within the precision of these results, the near-side peak appears to be significantly reduced in comparison to π^0-$h^\pm$, consistent with the expectations of section 2. Recent measurements in Au+Au and p+p have also indicated a demonstrated a similar absence of the near-side jet peak [12]. It is not yet possible to make strong statements about the away side jet peak until refinements to the analysis methods are implemented; moreover, it is likely that even when systematic errors are minimized,

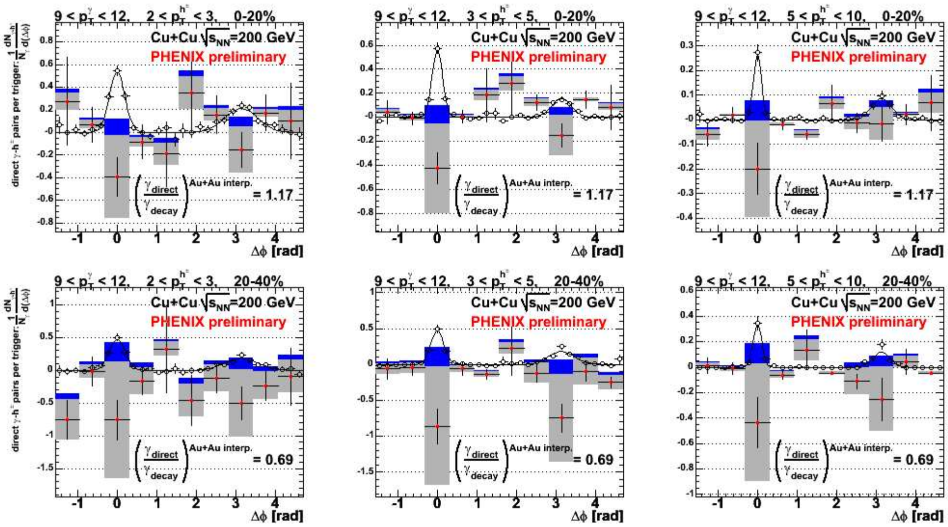

Fig. 5. Direct γ-jet correlations produced by the subtraction method for 9-12 GeV/c photons. The lighter error bands represent the systematic uncertainty from R_γ, and the darker error bands include systematic error from a bias in the determination of Y_{decay} as explained in the text. The open points are the π^0-$h^\pm$ per-trigger yields presented to give a reference for comparison.

more luminosity will be required to discriminate between detailed theoretical energy loss models proposed in e.g. [5]. However, a promising method of obtaining direct photon-hadron jet correlations has been presented, and the significant progress that has been made offers hope that more precise measurements will become available in the near future.

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